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14. ABSTRACT

Controls research under this program have concentrated on the development of hybrid control, impulsive dynamical systems, nonnegative dynamical systems, nonlinear switching control, and adaptive control with applications to aerospace systems. Specifically, a unified dynamical systems framework for a general class of nonlinear systems possessing left-continuous flows; that is, left continuous dynamical systems, was developed. These systems are shown to generalize virtually all existing notions of dynamical systems and include hybrid, impulsive, and switching dynamical systems as special cases.

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Hierarchical Robust and Adaptive Nonlinear Control Design

Final Report
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by

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Contents

1. Introduction

1.1. Research Objectives

As part of this research program we proposed the development of a general multiechelon hierarchical nonlinear switching control design framework that minimizes control law complexity subject to the achievement of control law robustness. In particular, we concentrated on hybrid control, impulsive dynamical systems, nonnegative dynamical systems, compartmental systems, nonlinear switching control, and adaptive control. Application areas included biological systems, physiological systems, pharmacological systems, ecological systems, vibration control of aerospace structures, spacecraft stabilization, and control of combustion in jet engines.

1.2. Overview of Research

Controls research by the Principal Investigator has concentrated on nonlinear control with applications to aerospace systems and biological and physiological systems [1-125]. In particular, a unified dynamical systems framework for a general class of systems possessing left-continuous flows; that is, left-continuous dynamical systems was developed. These systems are shown to generalize virtually all existing notions of dynamical systems and include hybrid, impulsive, and switching dynamical systems as special cases. Furthermore, we generalize dissipativity, passivity, and nonexpansivity theory to left-continuous dynamical systems. Specifically, the classical concepts of system storage functions and supply rates are extended to left-continuous dynamical systems providing a generalized hybrid system energy interpretation in terms of stored energy, dissipated energy over the continuous-time dynamics, and dissipated energy over the resetting events. The generalized dissipativity notions are then used to develop general stability criteria for feedback interconnections of left-continuous dynamical systems. These results generalize the positivity and small gain theorems to the case of left-continuous, hybrid, and impulsive dynamical systems. In addition, a unified framework for hybrid feedback optimal and inverse optimal control involving a hybrid nonlinear-nonquadratic performance functional is developed. It is shown that the hybrid cost functional can be evaluated in closed-form as long as the cost functional considered is related in a specific way to an underlying Lyapunov function that guarantees asymptotic stability of the nonlinear closed-loop left-continuous dynamical system. Furthermore, the Lyapunov function is shown to be a solution of a steady-state, hybrid Hamilton-Jacobi-Bellman equation.

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In addition, we developed a unified hierarchical hybrid nonlinear stabilization framework for hybrid port-controlled Hamiltonian systems. Specifically, we design passivity-based hierarchical hybrid controllers such that the total energy of the closed-loop hybrid system is the difference between the energy of the multi-agent hybrid system and the energy supplied by the controller. Hybrid passivity-based control architectures are extremely appealing since the control action has a clear *physical* energy interpretation over the continuous-time dynamics and the resetting instants. This feature can considerably simplify hardware/software implementation for hierarchical hybrid control systems.

Finally, a unified dynamical systems framework for stability and dissipativity theory for nonnegative dynamical systems is developed. Nonnegative dynamical system models are derived from mass and energy balance considerations that involve dynamic states whose values are nonnegative. These models are widespread in biological, physiological, and ecological sciences and play a key role in the understanding of these processes. In particular, we develop several results on stability, dissipativity, and feedback interconnections of linear and nonlinear nonnegative dynamical systems. Specifically, using *linear* Lyapunov functions we develop necessary and sufficient conditions for Lyapunov stability, semistability, and asymptotic stability for nonnegative systems. In addition, using *linear* storage functions and *linear* supply rates we extend the notions of dissipativity theory to nonnegative dynamical systems. These results are used to develop general stability criteria for feedback interconnections of nonnegative dynamical systems. Finally, an adaptive control framework for a class of nonlinear dynamical systems with state-dependent uncertainty is developed. The proposed framework guarantees global asymptotic stability of the closed-loop system states associated with the plant dynamics without requiring any knowledge of the system nonlinearities other than the assumption that they are continuous and lower bounded. Generalizations to the case where the system nonlinearities are unbounded are also considered. In the special case of matrix second-order systems with polynomial nonlinearities with unknown coefficients and unknown order, we provide a universal adaptive controller that guarantees closed-loop stability of the plant states. The aforementioned design frameworks were applied to pharmacokinetic systems, epidemic systems, population dynamics as well as to the control of thermoacoustic combustion instabilities in aeroengines.

1.3. Goals of this Report

The main goal of this report is to summarize the progress achieved under the program during the past three years. Since most of the technical results appeared or will soon appear in over 125 archival journal and conference publications, we shall only summarize these

results and remark on their significance and interrelationship.

2. Description of Work Accomplished

The following research accomplishments have been completed over the past three years.

2.1. Stability, Dissipativity, Feedback Interconnections, and Optimality of Hybrid Dynamical Systems

In the light of the increasingly complex nature of dynamical systems requiring controls, the predominant considerations in control law design for modern engineering systems have focused on general multiechelon hierarchical nonlinear switching control architectures that minimize control law complexity subject to the achievement of control law robustness. Multiechelon systems are classified as *hybrid* systems and typically possess a hierarchical structure characterized by continuous-time dynamics at the lower-level units and logical decision-making units at the higher-level of the hierarchy (see Figure 1). The logical decision making units serve to coordinate and reconcile the (sometimes competing) actions of the lower-level units. Due to their multiechelon hierarchical structure, hybrid dynamical systems are capable of simultaneously exhibiting continuous-time dynamics, discrete-time dynamics, logic commands, discrete-events, and resetting events. Such systems include dynamical switching systems, nonsmooth impact mechanical systems, biological systems, sampled-data systems, discrete-event systems, intelligent vehicle/highway systems, constrained mechanical systems, and flight control systems, to cite but a few examples. The mathematical descriptions of some of these systems can be characterized by impulsive differential equations [34, 35]. Impulsive dynamical systems can be viewed as a subclass of hybrid systems and consist of three elements; namely, a continuous-time differential equation, which governs the motion of the dynamical system between impulsive or resetting events; a difference equation, which governs the way the system states are instantaneously changed when a resetting event occurs; and a criterion for determining when the states of the system are to be reset.

Even though numerous results focusing on specific forms of hybrid systems have been developed in the literature, the development of a general model for hybrid dynamical systems has received little attention in the literature. In this research [33–35] we developed a unified dynamical systems framework for a general class of systems possessing left-continuous flows; that is, left-continuous dynamical systems. A left-continuous dynamical system is a precise mathematical object and is defined on the semi-infinite interval as a mapping between vector spaces satisfying an appropriate set of axioms and includes hybrid inputs and hybrid outputs
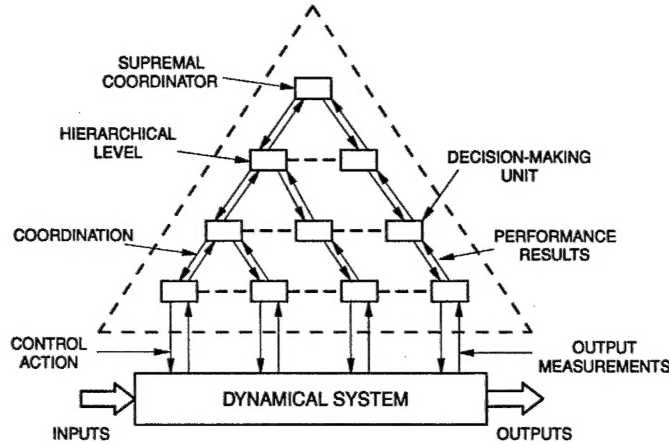
Figure 1: Multiechelon Dynamical System

that take their values in appropriate vector spaces. The notion of a left-continuous dynamical system introduced in [33] generalizes virtually all existing notions of dynamical systems and includes hybrid, impulsive, and switching dynamical systems as special cases. Furthermore, using generalized left-continuous storage functions and hybrid supply rates we extend the notions of classical dissipativity theory [48] and exponential dissipativity theory [48] to left-continuous dynamical systems. The overall approach provides an interpretation of a generalized hybrid energy balance of a left-continuous dynamical system in terms of the stored or, accumulated generalized energy, dissipated energy over the continuous-time dynamics, and dissipated energy at the resetting events. Furthermore, as in the continuous-time dynamical systems case possessing continuous flows, we show that the set of all possible storage functions of a left-continuous dynamical system forms a convex set and is bounded from below by the system's available stored generalized energy which can be extracted from the system, and bounded from above by the system's required generalized energy supply needed to transfer the system from an initial state of minimum generalized energy to a given state. In addition, in the case of nonlinear impulsive dynamical systems we developed extended Kalman-Yakubovich-Popov conditions in terms of the system dynamics for characterizing dissipativeness via system storage functions for impulsive dynamical systems.

Using the concepts of dissipativity and exponential dissipativity for left-continuous systems, we also developed feedback interconnection stability results for left-continuous dynamical systems. Specifically, general stability criteria are given for Lyapunov, asymptotic, and exponential stability of feedback left-continuous systems. In the case of quadratic hybrid supply rates involving net system power and input-output energy, these results generalize the positivity and small gain theorems to the case of left-continuous dynamical systems and hence hybrid and impulsive dynamical systems. In particular, we show that if the

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left-continuous dynamical systems $\mathcal{G}$ and $\mathcal{G}_c$ are dissipative (respectively, exponentially dissipative) with respect to quadratic hybrid supply rates corresponding to net system power, or weighted input and output energy, then the negative feedback interconnection of $\mathcal{G}$ and $\mathcal{G}_c$ is Lyapunov (respectively, asymptotically) stable.

Finally, we developed a hybrid feedback optimal control framework for nonlinear impulsive dynamical systems. The performance functional involves a continuous-time cost for addressing performance of the continuous-time system dynamics and a discrete-time cost for addressing performance at the resetting instants. Furthermore, the hybrid cost functional can be evaluated in closed-form as long as the nonlinear-nonquadratic cost functional considered is related in a specific way to an underlying Lyapunov function that guarantees asymptotic stability of the nonlinear closed-loop impulsive system. This Lyapunov function is shown to be a solution of a steady-state, hybrid Hamilton-Jacobi-Bellman equation and thus guaranteeing both optimality and stability of the feedback controlled impulsive system. The overall framework provides the foundation for extending linear-quadratic feedback control methods to nonlinear impulsive and hybrid dynamical systems. We note that the optimal control framework for impulsive dynamical systems developed in [35] is quite different from the quasivariational inequality methods for impulsive and hybrid control developed in the literature. Specifically, quasivariational methods do not guarantee asymptotic stability via Lyapunov functions and do not necessarily yield feedback controllers. In contrast, the proposed approach provides hybrid *feedback* controllers guaranteeing closed-loop stability via an underlying Lyapunov function.

2.2. An Invariance Principle for Nonlinear Hybrid and Impulsive Dynamical Systems

To analyze the stability of dynamical systems with impulsive effects, Lyapunov stability results have been presented in the literature. In particular, local and global asymptotic stability conclusions of an equilibrium point of a given impulsive dynamical system are provided if a smooth (at least C^1) positive-definite function of the nonlinear system states (Lyapunov function) can be constructed for which its time rate of change over the continuous-time dynamics is strictly negative and its difference over the resetting times is negative. However, unlike dynamical systems possessing continuous flows, Barbashin-Krasovskii-LaSalle-type invariant set stability theorems do not seem to have been addressed for impulsive dynamical systems. There appears to be (at least) two reasons for this state of affairs; namely, solutions of impulsive dynamical systems are *not* continuous in time and are *not* continuous functions of the system's initial conditions, which are two of the key properties needed to establish

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invariance of omega limit sets and hence an invariance principle.

In this research [34,45] we developed an invariance principle for left-continuous dynamical systems. In particular, invariant set theorems are derived wherein system trajectories converge to the largest invariant set of Lyapunov level surfaces of the left-continuous dynamical system. These systems are shown to specialize to hybrid systems and state-dependent nonlinear impulsive differential systems. Furthermore, in the case where the Lyapunov function is C^1 and defined on a compact positively invariant set (with respect to the nonlinear impulsive system), the largest invariant set is contained in a hybrid level surface composed of a union involving vanishing Lyapunov derivatives and Lyapunov differences of the system dynamics over the continuous-time trajectories and the resetting instants, respectively. In addition, if the Lyapunov derivative along the continuous-time system trajectories is negative semidefinite and no system trajectories can stay indefinitely at points where the function's derivative identically vanishes, then the system's equilibrium is asymptotically stable. These results provide less conservative conditions for examining the stability of state-dependent impulsive dynamical systems as compared to the classical results presented in the literature. Finally, the impulsive invariance principle can be used to establish the existence and investigate the stability of limit cycles and periodic orbits of impulsive systems.

2.3. On the Equivalence Between Dissipativity and Optimality of Nonlinear Hybrid Controllers

Modern complex engineering systems typically possess a multiechelon hierarchical architecture characterized by continuous-time dynamics at the lower levels of the hierarchy and discrete-time dynamics at the higher levels of the hierarchy. Hence, it is not surprising that hybrid systems have been the subject of intensive research over the past recent years. As discussed in Section 2.1, the mathematical descriptions of many of these systems can be characterized by impulsive differential equations.

In [34, 35] we developed a general framework for hybrid feedback systems by addressing stability, dissipativity, optimality, and inverse optimality of impulsive dynamical systems. In particular, in [35] we consider a hybrid feedback optimal control problem over an infinite horizon involving a hybrid nonlinear-nonquadratic performance functional. The performance functional involves a continuous-time cost for addressing performance of the continuous-time system dynamics and a discrete-time cost for addressing performance at the resetting instants. Furthermore, the hybrid cost functional can be evaluated in closed-form as long as the nonlinear-nonquadratic cost functional considered is related in a specific way to an underlying Lyapunov function that guarantees asymptotic stability of the nonlinear closed-loop

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hybrid system. This Lyapunov function is shown to be a solution to a steady-state, hybrid Hamilton-Jacobi-Bellman equation and thus guaranteeing both optimality and stability of the feedback controlled impulsive system. The overall framework provides the foundation for extending linear-quadratic feedback control methods to nonlinear impulsive dynamical systems.

For continuous-time nonlinear systems with continuous flows, the problem of guaranteed stability margins for optimal and inverse optimal regulators is well known. Specifically, nonlinear inverse optimal controllers that minimize a meaningful nonlinear-nonquadratic performance criterion involving a nonlinear-nonquadratic, nonnegative-definite function of the state and a quadratic positive definite function of the control are known to possess sector margin guarantees to component decoupled input nonlinearities lying in the conic sector $(\frac{1}{2}, \infty)$. These results also hold for disk margin guarantees where asymptotic stability of the closed-loop system is guaranteed in the face of a dissipative dynamic input operator. In addition, an equivalence between dissipativity with respect to a quadratic supply rate and optimality of a nonlinear regulator also holds.

In this research [30], we use the results of [34,35] to develop sufficient conditions for hybrid gain, sector, and disk margins guarantees for nonlinear hybrid dynamical systems controlled by optimal and inverse optimal hybrid regulators. Furthermore, we develop a hybrid counterpart of the return difference inequality for continuous-time systems to provide connections between dissipativity and optimality of nonlinear hybrid controllers. In particular, we show that unlike the case for continuous-time systems with continuous flows, the equivalence between dissipativity and optimality of hybrid controllers breaks down. However, we do show that optimal hybrid controllers imply dissipativity with respect to a quadratic supply rate.

2.4. A Generalization of Poincaré's Theorem to Hybrid and Impulsive Dynamical Systems

In certain dynamical systems and in particular mechanical and biological systems, system state discontinuities arise naturally. In a recent series of papers by the Principal Investigator [33, 45] a unified dynamical systems framework for a general class of systems possessing left-continuous flows; that is, left-continuous dynamical systems, was developed. A left-continuous dynamical system is a precise mathematical object that is defined on the semi-infinite interval as a mapping between vector spaces satisfying an appropriate set of axioms and includes hybrid and impulsive dynamical systems as special cases. Stability analysis of left-continuous dynamical systems is also considered in [33,45], with [45] presenting invariant set stability theorems for a class of left-continuous and impulsive dynamical systems. The

extension of the invariance principle to impulsive dynamical systems presented in [45] provides a powerful tool in analyzing the stability properties of periodic orbits and limit cycles of dynamical systems with impulse effects. However, the periodic orbit of a left-continuous dynamical system is a disconnected set in the n-dimensional state space making the construction of a Lyapunov-like function satisfying the invariance principle a daunting task for high-order nonlinear systems. In such cases, it becomes necessary to seek alternative tools to study the stability of periodic orbits of hybrid and impulsive dynamical systems, especially if the trajectory of the system can be relatively easily integrated.

In this research [37], we generalize Poincaré's theorem to left-continuous dynamical systems and hence to hybrid and impulsive dynamical systems. Specifically, we develop necessary and sufficient conditions for stability of periodic orbits based on the stability properties of a fixed point of a discrete-time dynamical system constructed from a Poincaré return map. As opposed to dynamical systems possessing continuous flows requiring the construction of a hyperplane that is transversal to a candidate periodic trajectory necessary for defining the return map, the resetting set which provides a criterion for determining when the states of the left-continuous dynamical system are to be reset provides a natural candidate for the transversal surface on which the Poincaré map of a left-continuous dynamical system can be defined. Hence, the Poincaré return map is defined by a subset of the resetting set that induces a discrete-time mapping from this subset onto the resetting set. This mapping traces the left-continuous trajectory of the left-continuous dynamical system from a point on the resetting set to its next corresponding intersection with the resetting set. In the case of impulsive dynamical systems possessing sufficiently smooth resetting manifolds, we show the Poincaré return map can be used to establish a relationship between the stability properties of an impulsive dynamical system with periodic solutions and the stability properties of an equilibrium point of an $(n-1)$th-order discrete-time system. These results have been recently employed to analyze the periodic orbits for the verge and folio clock escapement mechanism [56] which exhibits impulsive dynamics.

2.5. A Unification Between Partial Stability of State-Dependent Impulsive Systems and Stability Theory of Time-Dependent Impulsive Systems

As discussed in Section 2.1, impulsive differential equations are ideal in describing the dynamics of hybrid systems which typically possess a multiechelon hierarchical architecture characterized by continuous-time dynamics at the lower levels of the hierarchy and discrete-time dynamics at the higher levels of the hierarchy. Since hybrid dynamical systems involve

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an *interacting* countable collection of dynamical systems wherein the dynamic states are not independent of one another and yet not all system states are of equal precedence, *partial stability*; that is, stability with respect to part of the system's states, is often necessary. In this research [38], we build on the stability results of impulsive dynamical systems developed in [33,34,45] to present partial stability theorems for nonlinear impulsive dynamical systems.

Since the stability analysis of general impulsive dynamical systems can be quite involved, two distinct forms of the resetting set are typically considered [34]. In the first case, the resetting set is defined by a region in the state space and is independent of time. These systems are called *state-dependent impulsive dynamical systems* [34]. In the second case, the resetting set is defined by a prescribed sequence of times that are independent of the system state. These systems are thus called *time-dependent impulsive dynamical systems* [34]. Since state-dependent impulsive dynamical systems are time-invariant systems and time-dependent impulsive dynamical systems are time-varying systems, stability theory for these systems are often separated. Using the partial stability results we additionally present a unification between partial stability of (autonomous) state-dependent impulsive dynamical systems and stability theory for (nonautonomous) time-dependent impulsive dynamical systems. This unification allows for stability theory of time-dependent impulsive dynamical systems to be presented as a special case of partial stability theory for state-dependent impulsive dynamical systems.

2.6. Energy-Based Control for Hybrid Hamiltonian Systems

Modern complex engineering systems involve multiple modes of operation placing stringent demands on controller design and implementation of increasing complexity. Such systems typically possess a multiechelon hierarchical *hybrid* control architecture characterized by continuous-time dynamics at the lower levels of the hierarchy and discrete-time dynamics at the higher-levels of hierarchy. The lower-level units directly interact with the dynamical system to be controlled while the higher-level units receive information from the lower-level units as inputs and provide (possibly discrete) output commands which serve to coordinate and reconcile the (sometimes competing) actions of the lower-level units. The hierarchical controller organization reduces processor cost and controller complexity by breaking up the processing task into relatively small pieces and decomposing the fast and slow control functions. Typically, the higher-level units perform logical checks that determine system mode operation, while the lower-level units execute continuous-variable commands for a given system mode of operation. The mathematical description of many of these systems can be characterized by impulsive differential equations. Furthermore, since certain dynam-

ical systems such as telecommunication systems, transportation systems, biological systems, physiological systems, power systems, and network systems involve high-level, abstract hierarchies with input-output properties related to conservation, dissipation, and transport of mass and/or energy, they can be modeled as *hybrid port-controlled Hamiltonian systems.*

In this research [63], we use the stability, dissipativity, and optimality framework for hybrid and impulsive dynamical systems developed in [34,35] to develop an energy-based hybrid feedback control framework for nonlinear impulsive port-controlled Hamiltonian systems that preserves the physical hybrid Hamiltonian structure at the closed-loop level. Since the hybrid Hamiltonian structure is preserved at the closed-loop level, the passivity-based controller is *robust* with respect to unmodeled passive dynamics. Furthermore, passivity-based control architectures are extremely appealing since the control action has a clear *physical* energy interpretation which can considerably simplify controller implementation.

2.7. Hybrid Adaptive Control for Nonlinear Impulsive Dynamical Systems

Modern complex engineering systems involve multiple modes of operation placing stringent demands on controller design and implementation of increasing complexity. Such systems typically possess a multiechelon hierarchical *hybrid* control architecture characterized by continuous-time dynamics at the lower levels of the hierarchy and discrete-time dynamics at the higher levels of the hierarchy. The lower-level units directly interact with the dynamical system to be controlled while the higher-level units receive information from the lower-level units as inputs and provide (possibly discrete) output commands which serve to coordinate and reconcile the (sometimes competing) actions of the lower-level units. The hierarchical controller organization reduces processor cost and controller complexity by breaking up the processing task into relatively small pieces and decomposing the fast and slow control functions. Typically, the higher-level units perform logical checks that determine system mode operation, while the lower-level units execute continuous-variable commands for a given system mode of operation. The mathematical description of many of these systems can be characterized by impulsive differential equations [34].

The ability of developing a hierarchical nonlinear integrated hybrid control-system design methodology for robust, high performance controllers satisfying multiple design criteria and real-world hardware constraints is imperative in light of the increasingly complex nature of dynamical systems requiring controls such as advanced high performance tactical fighter aircraft, variable-cycle gas turbine engines, biological and physiological systems, sampled-data systems, discrete-event systems, intelligent vehicle/highway systems, and flight control

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systems, to cite but a few examples. The inherent severe nonlinearities and uncertainties of these systems and the increasingly stringent performance requirements required for controlling such modern complex embedded systems necessitates the development of adaptive nonlinear hybrid control methodologies.

Even though adaptive control algorithms have been extensively developed in the literature for both continuous-time and discrete-time systems, hybrid adaptive control algorithms for hybrid dynamical systems are nonexistent. In this research [69, 120], we develop a direct hybrid adaptive control framework for nonlinear uncertain impulsive dynamical systems. In particular, a Lyapunov-based hybrid adaptive control framework is developed that guarantees partial asymptotic stability of the closed-loop hybrid system; that is, asymptotic stability with respect to part of the closed-loop system states associated with the hybrid plant dynamics. Furthermore, the remainder of the state associated with the adaptive controller gains is shown to be Lyapunov stable. In the case where the nonlinear hybrid system is represented in a *hybrid normal form*, we construct nonlinear hybrid controllers *without* requiring knowledge of the hybrid system dynamics. Finally, we note that since impulsive dynamical systems involve a hybrid formulation of continuous-time and discrete-time dynamics, our results build on our adaptive control algorithms for continuous-time and discrete-time systems presented in [36, 66].

2.8. Active Control of Combustion Instabilities via Hybrid Resetting Controllers

Engineering applications involving steam and gas turbines and jet and ramjet engines for power generation and propulsion technology involve combustion processes. Due to the inherent coupling between several intricate physical phenomena in these processes involving acoustics, thermodynamics, fluid mechanics, and chemical kinetics, the dynamic behavior of combustion systems is characterized by highly complex nonlinear models [10]. The unstable dynamic coupling between heat release in combustion processes generated by reacting mixtures releasing chemical energy and unsteady motions in the combustor develop acoustic pressure and velocity oscillations which can severely impact operating conditions and system performance [10]. These pressure oscillations, known as thermoacoustic instabilities, often lead to high vibration levels causing mechanical failures, high levels of acoustic noise, high burn rates, and even component melting. Hence, the need for active control to mitigate combustion induced pressure instabilities is severe.

Utilizing a time-averaged combustion model for capturing thermoacoustic instabilities, we developed hybrid resetting controllers to mitigate combustion induced pressure insta-
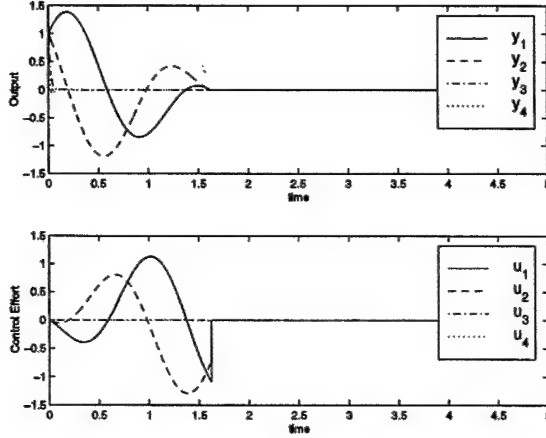
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Figure 2: These plots illustrate finite-time stabilization (i.e., finite settling time performance) of a two-mode combustion system controlled by a state-dependent hybrid resetting controller. The time history of the pressure and pressure rate amplitudes of both modes are shown in the upper plot, while the time history of the control force is force given in the lower plot. The pressure and pressure rate amplitudes settle to the origin at the first resetting time and remain there for all future time.

bilities in combustion systems [82, 90, 91]. The hybrid resetting controller can be viewed as a specialized technique for severing the coupling between the acoustics and unsteady combustion to effectively enhance the removal of energy in the combustor. In particular, significant modal energy dissipation is achieved via the hybrid resetting controller to suppress thermoacoustic oscillations. The framework in [34, 35] is used to design two kinds of hybrid resetting controllers; namely, time-dependent and input/state-dependent resetting controllers. The overall framework demonstrates that hybrid resetting controllers provide an extremely efficient mechanism for dissipating energy in combustion processes (see Figure 2).

2.9. Direct Adaptive Control for Nonlinear Uncertain Systems with Exogenous Disturbances

Unavoidable discrepancies between system models and real-world systems can result in degradation of control-system performance including instability. Thus, it is not surprising that one of the fundamental problems in feedback control design is the ability of the control system to guarantee robustness with respect to system uncertainties in the design model. To this end, adaptive control along with robust control theory have been developed to address the problem of system uncertainty in control-system design. The fundamental differences between adaptive control design and robust control theory can be traced to the modeling and treatment of system uncertainties as well as the controller architecture structures. In particular, adaptive control is based on constant linearly parameterized system uncertainty models

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of a known structure but unknown variation, while robust control is predicated on structured and/or unstructured linear or nonlinear (possibly time-varying) operator uncertainty models consisting of bounded variation. Hence, for systems with constant real parameter uncertainty, robust controllers will unnecessarily sacrifice performance whereas adaptive feedback controllers can tolerate far greater system uncertainty levels to improve system performance. Furthermore, in contrast to fixed-gain robust controllers, which maintain specified constants within the feedback control law to *sustain* robust performance, adaptive controllers directly or indirectly adjust feedback gains to maintain closed-loop stability and *improve* performance in the face of system uncertainties. Specifically, indirect adaptive controllers utilize parameter update laws to identify unknown system parameters and adjust feedback gains to account for system variation, while direct adaptive controllers directly adjust the controller gains in response to plant variations.

In this research [36], we develop a direct adaptive control framework for adaptive stabilization, disturbance rejection, and command following of multivariable nonlinear uncertain systems with exogenous disturbances. In particular, a Lyapunov-based direct adaptive control framework is developed that requires a matching condition on the system disturbance and guarantees partial asymptotic stability of the closed-loop system; that is, asymptotic stability with respect to part of the closed-loop system states associated with the plant. Furthermore, the remainder of the state associated with the adaptive controller gains is shown to be Lyapunov stable. In the case where the nonlinear system is represented in normal form with input-to-state stable zero dynamics, we construct nonlinear adaptive controllers *without* requiring knowledge of the system dynamics or the system disturbance. In addition, the proposed nonlinear adaptive controllers also guarantee asymptotic stability of the system state if the system dynamics are unknown *and* the input matrix function is parameterized by an unknown constant sign definite matrix. Finally, we generalize the aforementioned results to uncertain nonlinear systems with exogenous L_2 disturbances. In this case, we remove the matching condition on the system disturbance. In addition, the proposed framework guarantees that the closed-loop nonlinear input-output map from uncertain exogenous L_2 disturbances to system performance variables is nonexpansive (gain bounded) and the solution of the closed-loop system is partially asymptotically stable. The proposed adaptive controller thus addresses the problem of disturbance rejection for nonlinear uncertain systems with bounded energy (square-integrable) L_2 signal norms on the disturbances and performance variables. This is clearly relevant for uncertain systems with poorly modeled disturbances which possess significant power within arbitrarily small bandwidths.

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2.10. Robust Adaptive Control for Nonlinear Uncertain Systems

In [36], a direct nonlinear adaptive control framework for adaptive stabilization, disturbance rejection, and command following was developed. In particular, a Lyapunov-based direct adaptive control framework was developed that guarantees partial asymptotic stability of the closed-loop system; that is, asymptotic stability with respect to part of the closed-loop system states associated with the plant. Furthermore, the remainder of the state associated with the adaptive controller gains was shown to be Lyapunov stable. In the case where the nonlinear system was represented in normal form with input-to-state stable zero dynamics, the nonlinear adaptive controller was constructed *without* requiring knowledge of the system dynamics.

As is the case in the adaptive control literature, the system errors in [36] are captured by a constant linearly parameterized uncertainty model of a known structure but unknown variation. This uncertainty characterization allows the system nonlinearities to be parameterized by a finite linear combination of basis functions within a class of function approximators such as rational functions, spline functions, radial basis functions, sigmoidal functions, and wavelets. However, this linear parametrization of basis functions cannot exactly capture the unknown system nonlinearity. In this research [44], we generalize the results of [36] to nonlinear uncertain systems with constant linearly parameterized uncertainty and nonlinear state-dependent uncertainty. Specifically, we consider a robust adaptive control problem that guarantees asymptotic robust stability of the system states in the face of structured uncertainty with unknown variation *and* structured (possibly nonlinear) parametric uncertainty with bounded variation. Hence, the overall adaptive control framework captures the residual approximation error inherent in linear parameterizations of system uncertainty via basis functions.

2.11. A Lyapunov-Based Adaptive Control Framework for Discrete-Time Nonlinear Systems with Exogenous Disturbances

The purpose of feedback control is to achieve desirable system performance in the face of system uncertainty and system disturbances. Although system identification can reduce uncertainty to some extent, residual modeling discrepancies always remain. Controllers must therefore be robust to achieve desired disturbance rejection and/or tracking performance requirements in the presence of such modeling uncertainty. To this end, adaptive control along with robust control theory have been developed to address the problem of system

performance in the face of system uncertainty in control-system design without excessive reliance on system models.

Adaptive controllers directly or indirectly adjust feedback gains to maintain closed-loop stability and improve performance in the face of system errors. Specifically, indirect adaptive controllers utilize parameter update laws to estimate unknown system parameters and adjust feedback gains to account for system variation, while direct adaptive controllers directly adapt the controller gains in response to system variations. Even though adaptive control algorithms have been developed in the literature for both continuous-time and discrete-time systems, the majority of the discrete-time results are based on recursive least-squares and least mean squares algorithms with primary focus on state convergence. Alternatively, Lyapunov-based adaptive controllers have been developed for continuous-time systems guaranteeing asymptotic stability of the system states. However, the literature on discrete-time adaptive disturbance rejection control using Lyapunov methods is virtually nonexistent.

In this research [66,109], we develop a Lyapunov-based direct adaptive control framework for adaptive stabilization, disturbance rejection, and command following of multivariable discrete-time nonlinear uncertain systems with exogenous bounded amplitude disturbances and ℓ_2 disturbances. These results are analogous to the recent continuous-time adaptive disturbance rejection results in [36] for continuous-time nonlinear uncertain systems. Specifically, a Lyapunov-based direct adaptive control framework is developed that guarantees partial asymptotic stability of the closed-loop system; that is, asymptotic stability with respect to part of the closed-loop system states associated with the plant. Furthermore, in the case where the nonlinear system is represented in normal form, the nonlinear discrete-time adaptive controller is constructed *without* requiring knowledge of the system dynamics or system disturbances. In the case where the system disturbances are ℓ_2 disturbances, the proposed framework guarantees that the closed-loop nonlinear input-output map from uncertain exogenous ℓ_2 disturbances to system performance variables is nonexpansive and the solution of the closed-loop system is partially asymptotically stable. The proposed adaptive controller thus addresses the problem of disturbance rejection for nonlinear uncertain discrete-time systems with bounded energy (square-summable) ℓ_2 signal norms on the disturbances and performance variables.

2.12. Direct Discrete-Time Adaptive Control with Guaranteed Parameter Error Convergence

Adaptive control algorithms have been extensively developed in the literature for both continuous-time and discrete-time systems. A salient difference between continuous-time and

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discrete-time adaptive controllers is that the majority of the discrete-time results are based on recursive least-squares and least mean squares algorithms with primary focus on state convergence. In this research [70], we develop a direct adaptive nonlinear tracking control framework based on *semidefinite* or *partial* Lyapunov functions for discrete-time nonlinear uncertain systems. The proposed framework guarantees attraction of the closed-loop tracking error dynamics in the face of parametric system uncertainty. In addition, parameter error convergence is also guaranteed when a generic geometric constraint on the update error gain matrix function holds. This condition is shown to be consistent with the notion of persistent excitation in the adaptive control and system identification literature.

2.13. Adaptive Control for Nonlinear Systems with State-Dependent Uncertainty

In light of the increasingly complex and highly uncertain nature of dynamical systems requiring controls, it is not surprising that reliable system models for many high performance engineering applications are unavailable. In the face of such high levels of system uncertainty, adaptive controllers are clearly appropriate since they can tolerate high levels of system errors to improve system performance. However, a fundamental limitation of adaptive control is the fact that system errors are captured by constant linearly parameterized uncertainty models of a known structure but unknown variation. If the system uncertainty is nonlinear in the uncertain parameters or the system uncertainty is nonlinearly dependent on the system states, then adaptive controllers predicated on a constant linearly (over)parameterized model will unnecessarily sacrifice system performance, and in some cases lead to instability.

In this research [43], we develop a novel adaptive control framework that does not require any parametrization of the state-dependent system uncertainty. In particular, for a class of nonlinear multivariable *matrix* second-order uncertain dynamical systems with state-dependent uncertainty we develop a nonlinear adaptive control framework that guarantees global partial asymptotic stability of the closed-loop system; that is, global asymptotic stability with respect to part of the closed-loop system states associated with the plant. This is achieved without requiring any knowledge of the system nonlinearities other than the assumption that they are continuous and lower bounded. Next, we extend our main result to the case where the system nonlinearities are unbounded. Using this result, we provide a universal adaptive controller that guarantees asymptotic stability for the case of matrix second-order systems with polynomial nonlinearities with unknown coefficients and *unknown order*. The class of systems represented by our framework includes nonlinear vibrational systems, as well as multivariable nonlinear dynamical systems with sign varying; that is,

nondissipative, generalized stiffness and damping operators.

2.14. Direct Adaptive Control for Nonlinear Matrix Second-Order Systems with Time-Varying and Sign-Indefinite Damping and Stiffness Operators

For a class of *nonlinear* multivariable *matrix* second-order uncertain dynamical systems, with time-varying and sign-indefinite damping and stiffness operators, we develop a non-linear adaptive control framework that guarantees global partial asymptotic stability of the closed-loop system; that is, global asymptotic stability with respect to part of the closed-loop system states associated with the plant [71, 122]. This is achieved without requiring any knowledge of the system nonlinearities other than the assumption that they are continuous and bounded. The class of systems represented by our framework includes nonlinear vibrational systems, as well as multivariable nonlinear dynamical systems with sign-varying; that is, nondissipative, generalized stiffness and damping time-varying operators. Finally, we note that a similar adaptive control framework for nonlinear uncertain matrix second-order systems was considered in [43]. The results presented in [43] however only address *time-invariant*, sign-indefinite stiffness and damping operator uncertainty. In this case, the unknown system nonlinearities need only be continuous and lower bounded as opposed to continuous and bounded.

2.15. Nonnegative Dynamical Systems in Biology, Medicine, and Ecology

With the increasing mergence of engineering disciplines and biological and medical sciences, it is not surprising that dynamical systems theory has played an increasing role in the understanding of biological and physiological processes. With this unification it has rapidly become apparent that mathematical modeling and dynamical systems theory is the key thread that ties together these diverse disciplines. The dynamical models of many biological and physiological processes such as pharmacokinetics, metabolic systems, epidemiology, biochemical reactions, endocrine systems, and lipoprotein kinetics are derived from mass and energy balance considerations that involve dynamic states whose values are nonnegative. Hence, it follows from physical considerations that the state trajectory of such systems remain in the nonnegative orthant of the state space for nonnegative initial conditions. Such systems are commonly referred to as *nonnegative dynamical systems* in the literature. A subclass of nonnegative dynamical systems are *compartmental systems* whose dynamical models
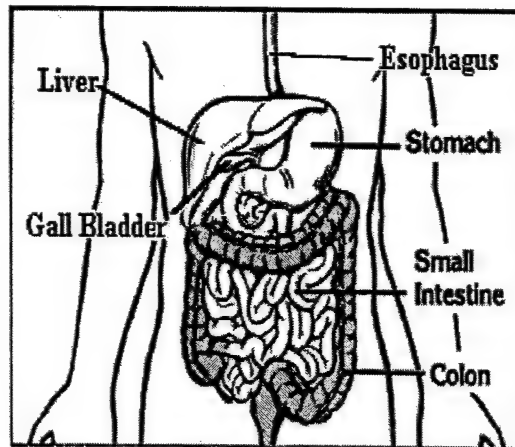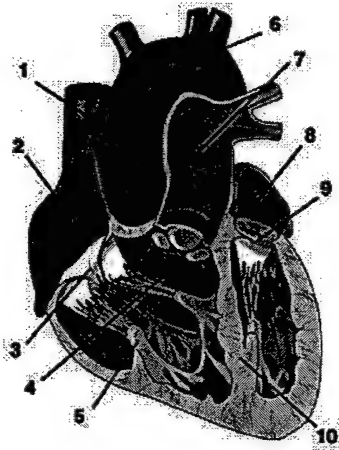
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Figure 3: Models for blood flow through the heart as well as the anatomy of the human body can be captured by compartmental systems.

are characterized by conservation laws (e.g., mass and energy) capturing the exchange of material between coupled macroscopic subsystems known as compartments (see Figure 3). Each compartment is assumed to be kinetically homogeneous; that is, any material entering the compartment is instantaneously mixed with the material of the compartment. The range of applications of nonnegative systems and compartmental systems is not limited to biological and medical systems. Their usage include chemical reaction systems, queuing systems, large-scale systems, stochastic systems (whose state variables represent probabilities), ecological systems, and economic systems, to cite but a few examples.

Even though numerous results focusing on compartmental systems have been developed in the literature, the development of nonnegative dynamical systems theory has received far less attention. In this research [57, 105], we develop several basic mathematical results on stability, dissipativity, and feedback interconnections of linear and nonlinear nonnegative dynamical systems. Linear nonnegative dynamical systems are of major importance in biological and physiological systems since almost the entire field of distribution of tracer labeled materials in steady state systems can be captured by linear nonnegative systems. Alternatively, many applications in life sciences give rise to nonlinear nonnegative dynamical systems. These include metabolic pathways, membrane transports, pharmacodynamics, epidemiology, and ecology. Using *linear* Lyapunov functions, we develop necessary and sufficient conditions for Lyapunov stability, semistability; that is, system trajectory convergence to Lyapunov stable equilibrium points, and asymptotic stability for linear nonnegative dynamical systems. Extensions to nonlinear nonnegative dynamical systems are also provided. The consideration of a linear Lyapunov function leads to a *new* Lyapunov-like equation for examining the stability of linear nonnegative systems. This Lyapunov-like equation is ana-

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lyzed using nonnegative matrix theory. The motivation for using a linear Lyapunov function follows from the fact that the state of a nonnegative dynamical system is nonnegative and hence a linear Lyapunov function is a valid Lyapunov function candidate. This considerably simplifies the stability analysis of nonnegative dynamical systems. For compartmental systems, a linear Lyapunov function corresponds to the total mass of the system.

Dissipativity theory has been extensively developed for the analysis and design of control systems for engineering systems using input-output system descriptions based on energy related considerations without the consideration of nonnegative and compartmental models. Since biological and physiological systems have numerous input-output properties related to conservation, dissipation, and transport of mass and energy, it seems natural to extend dissipativity theory to nonnegative and compartmental models which themselves behave in accordance to conservation laws. Using *linear* storage functions and *linear* supply rates we extend the notions of classical dissipativity theory and exponential dissipativity theory [48] to linear and nonlinear nonnegative dynamical systems. The overall approach provides a new interpretation of a mass balance for nonnegative systems with linear supply rates and linear storage functions. Specifically, we show that dissipativity of a nonnegative dynamical system involving a linear storage function and a linear supply rate implies that the system mass transport is always less than or equal to the difference between the system flux input and the system flux output. In addition, we develop *new* Kalman-Yakubovich-Popov equations for nonnegative systems for characterizing dissipativeness with linear storage functions and linear supply rates.

Feedback systems are pervasive in nature and can be found almost everywhere in living systems. In particular, control at the intercellular level, DNA replication and cell division, control of gene expression, control of enzyme activity, control at the organ system and organism level, humoral control, neural control, and regulation in biological systems all involve feedback systems. To analyze these complex nonnegative systems, the concepts of dissipativity and exponential dissipativity with linear storage functions and linear supply rates are used to develop feedback interconnection stability results for nonnegative dynamical systems. General stability criteria are given for Lyapunov, semi, and asymptotic stability of feedback linear and nonlinear nonnegative systems. These results can be viewed as a generalization of the positivity and the small gain theorems to nonnegative systems with linear storage functions and linear supply rates. A key observation of theses results is that unlike the classical results on positivity and the small gain theorems requiring *negative* feedback interconnections, *positive* feedback interconnections are required in order to assure that the resulting feedback system is a nonnegative dynamical system.

2.16. Stability and Dissipativity Theory for Nonnegative and Compartmental Dynamical Systems with Time Delay

Modern complex engineering systems are highly interconnected and mutually interdependent, both physically and through a multitude of information and communication networks. By properly formulating these systems in terms of subsystem interaction and energy/mass transfer, the dynamical models of many of these systems can be derived from mass, energy, and information balance considerations that involve dynamic states whose values are nonnegative. Hence, it follows from physical considerations that the state trajectory of such systems remains in the nonnegative orthant of the state space for nonnegative initial conditions. As noted in Section 2.15, such systems are commonly referred to as nonnegative dynamical systems in the literature. Compartmental systems, a subclass of nonnegative dynamical systems, involve dynamical models that are characterized by conservation laws (e.g., mass and energy) capturing the exchange of material between coupled macroscopic subsystems known as compartments. Each compartment is assumed to be kinetically homogeneous; that is, any material entering the compartment is instantaneously mixed with the material of the compartment. The range of applications of nonnegative systems and compartmental systems is not limited to complex engineering systems. Their usage includes biological and physiological systems, chemical reaction systems, queuing systems, large-scale systems, stochastic systems (whose state variables represent probabilities), ecological systems, economic systems, demographic systems, telecommunication systems, transportation systems, power systems, heat transfer systems, and structural vibration systems, to cite but a few examples. A key physical limitation of such systems is that transfers between compartments are not instantaneous and realistic models for capturing the dynamics of such systems should account for material, energy, or information in transit between compartments. Hence, to accurately describe the evolution of the aforementioned systems, it is necessary to include in any mathematical model of the system dynamics some information of the past system states. This of course leads to (infinite-dimensional) delay dynamical systems.

In this research [60, 73], we develop necessary and sufficient conditions for time-delay nonnegative and compartmental dynamical systems. Specifically, using *linear* Lyapunov-Krasovskii functionals we develop necessary and sufficient conditions for asymptotic stability of linear nonnegative dynamical systems with time delay. The consideration of a linear Lyapunov-Krasovskii functional leads to a *new* Lyapunov-like equation for examining stability of time delay nonnegative dynamical systems. The motivation for using a linear Lyapunov-Krasovskii functional follows from the fact that the (infinite-dimensional) state of a retarded nonnegative dynamical system is nonnegative and hence a linear Lyapunov-

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Krasovskii functional is a valid candidate Lyapunov-Krasovskii functional. For a time delay compartmental system, a linear Lyapunov-Krasovskii functional is shown to correspond to the total mass of the system at a given time plus the integral of the mass flow in transit between compartments over the time intervals it takes for the mass to flow through the intercompartmental connections.

Next, exploiting the input-output properties related to conservation, dissipation, and transport of mass and energy in nonnegative and compartmental dynamical systems, we develop a *new* notion of classical dissipativity theory for nonnegative dynamical systems with time delay. Specifically, using linear storage functionals with linear supply rates we develop sufficient conditions for dissipativity of nonnegative dynamical systems with time delay. The motivation for using linear storage functionals and linear supply rates follows from the fact that the (infinite-dimensional) state as well as the inputs and outputs of retarded nonnegative dynamical systems are nonnegative. The consideration of linear storage functionals and linear supply rates leads to new Kalman-Yakubovich-Popov equations for characterizing dissipativity of nonnegative systems with time delay. For a time delay compartmental system, a linear storage functional is shown to correspond to the total mass of the system at a given time plus the integral of the mass flow in transit between compartments over the time intervals it takes for the mass to flow through the intercompartmental connections. In this case dissipativity implies that the total system mass transport is equal to the supplied system flux minus the expelled system flux. Finally, using the concepts of dissipativity for retarded nonnegative dynamical systems, we develop feedback interconnection stability results for nonnegative systems with time delay. In particular, general stability criteria are given for Lyapunov and asymptotic stability of feedback nonnegative dynamical systems with time delays.

2.17. On Nonoscillation and Monotonicity of Solutions of Non-negative and Compartmental Dynamical Systems

As discussed in Section 2.15, nonnegative and compartmental systems are essential in capturing the phenomenological behavior of a wide range of dynamical systems involving dynamic states whose values are nonnegative. Compartmental systems are widely used as models of biological and physiological processes, such as metabolic pathways, tracer kinetics, pharmacokinetics, epidemic dynamics, and ecological systems. These systems are characterized by conservation laws that describe the interchange of mass or energy between homogeneous subsystems known as compartments. While compartmental systems have wide applicability in biology and medicine, their use in the specific field of pharmacokinetics is

particularly noteworthy.

The goal of pharmacokinetic analysis often is to characterize the kinetics of drug disposition in terms of the parameters of a compartmental model. This is accomplished by postulating a model, collecting experimental data (typically drug concentrations in blood as a function of time), and then using statistical analysis to estimate parameter values which best describe the data. Differences between experimental data and that predicted by the model are attributed to measurement noise. Because the ultimate disposition of exogenous drugs is metabolism and elimination from the body, it is frequently assumed that drug concentrations will monotonically decline after discontinuation of drug administration. However, compartmental systems may admit non-monotonic solutions (e.g., underdamped oscillations); that is, they can predict drug concentrations which do not decay monotonically with time after discontinuation of drug administration. Hence, it would be useful to identify compartmental systems which guarantee monotonicity of solutions in order to avoid attributing error (differences between model predictions and experimental data) to random noise, when the problem is in fact model-misspecification. Similar considerations are also relevant to the other applications of nonnegative and compartmental dynamical systems. In this research [61, 112], we present necessary and sufficient conditions for identifying nonnegative and compartmental dynamical systems that only admit nonoscillatory and monotonic solutions.

2.18. Hybrid Nonnegative and Compartmental Dynamical Systems

As discussed in Section 2.15, nonnegative and compartmental systems are essential in capturing the phenomenological features of a wide range of dynamical systems involving dynamic states whose values are nonnegative. These systems are derived from mass and energy balance considerations and are comprised of homogeneous interconnected macroscopic subsystems or compartments which exchange variable quantities of material via intercompartmental flow laws. Since biological and physiological systems have numerous input-output properties related to conservation, dissipation, and transport of mass and energy, nonnegative and compartmental systems are remarkably effective in describing the essential features of these dynamical systems.

Complex biological and physiological systems typically possess a multiechelon hierarchical hybrid structure characterized by continuous-time dynamics at the lower-level units and logical decision-making units at the higher-level of the hierarchy. The logical decision making units serve to coordinate and reconcile the (sometimes competing) actions of the lower-

level units. Due to their multiechelon hierarchical structure, hybrid dynamical systems are capable of simultaneously exhibiting continuous-time dynamics, discrete-time dynamics, logic commands, discrete-events, and resetting events. Hence, hybrid dynamical systems involve an *interacting* countable collection of dynamical systems wherein control actions are not independent of one another and yet not all control actions are of equal precedence. For example, in physiological systems the blood pressure and blood flow to different tissues of the human body are controlled to provide sufficient oxygen to the cells of each organ. Certain organs such as the kidneys normally require higher blood flows than is necessary to satisfy basic oxygen needs. However, during stress (such as hemorrhage) when perfusion pressure falls, perfusion of certain regions (e.g., brain and heart) takes precedence over perfusion of other regions and hierarchical controls (overriding controls) shut down flow to these other regions. The mathematical descriptions of many hybrid dynamical systems can be characterized by impulsive differential equations [34, 35].

In this research [49], we developed several basic mathematical results on stability and dissipativity of hybrid nonnegative and compartmental dynamical systems. Specifically, using *linear* Lyapunov functions we develop sufficient conditions for Lyapunov stability and asymptotic stability for hybrid nonnegative dynamical systems. The consideration of a linear Lyapunov function leads to a *new* set of Lyapunov-like equations for examining the stability of linear impulsive nonnegative systems. The motivation for using a linear Lyapunov function follows from the fact that the state of a nonnegative dynamical system is nonnegative and hence a linear Lyapunov function is a valid Lyapunov function candidate.

Next, using *linear* and *nonlinear* storage functions with *linear* hybrid supply rates we develop *new* notions of classical dissipativity theory and exponential dissipativity theory for hybrid nonnegative dynamical systems. The overall approach provides a new interpretation of a mass balance for hybrid nonnegative systems with linear hybrid supply rates and linear and nonlinear storage functions. Specifically, we show that dissipativity of a hybrid nonnegative dynamical system involving a linear storage function and a linear hybrid supply rate implies that the system mass transport (respectively, change in system mass) is equal to the supplied system flux (respectively, mass) over the continuous-time dynamics (respectively, the resetting instants) minus the expelled system flux (respectively, mass) over the continuous-time dynamics (respectively, the resetting instants). In addition, we develop *new* Kalman-Yakubovich-Popov equations for hybrid nonnegative systems for characterizing dissipativity with linear and nonlinear storage functions and linear hybrid supply rates. Finally, using concepts of dissipativity and exponential dissipativity for hybrid nonnegative dynamical systems, we develop feedback interconnection stability results for nonlinear nonnegative impulsive systems. Specifically, general stability criteria are given for Lyapunov and

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asymptotic stability of feedback hybrid nonnegative systems. These results can be viewed as a generalization of the positivity and the small gain theorems to hybrid nonnegative systems with linear supply rates involving net input-output system flux.

2.19. Adaptive Control for General Anesthesia and Intensive Care Unit Sedation

Even though advanced robust and adaptive control methodologies have been (and are being) extensively developed for highly complex engineering systems, modern active control technology has received far less consideration in medical systems. The main reason for this state of affairs is the steep barriers to communication between mathematics/control engineering and medicine. However, this is slowly changing and there is no doubt that control-system technology has a great deal to offer medicine. For example, critical care patients, whether undergoing surgery or recovering in intensive care units, require drug administration to regulate key physiological (state) variables (e.g., blood pressure, temperature, glucose, degree of consciousness, etc.) within desired levels. The rate of infusion of each administered drug is *critical*, requiring constant monitoring and frequent adjustments. Open-loop control (manual control) by clinical personnel can be very tedious, imprecise, time consuming, and often of poor quality. Hence, the need for active control (closed-loop control) in medical systems is severe; with the potential in improving the quality of medical care as well as curtailing the increasing cost of health care.

The complex highly uncertain and hostile environment of surgery places stringent performance requirements for closed-loop set-point regulation of physiological variables. For example, during cardiac surgery, blood pressure control is vital and is subject to numerous highly uncertain exogenous disturbances. Vasoactive and cardioactive drugs are administered resulting in large disturbance oscillations to the system (patient). The arterial line may be flushed and blood may be drawn, corrupting sensor blood pressure measurements. Low anesthetic levels may cause the patient to react to painful stimuli, thereby changing system (patient) response characteristics. The flow rate of vasodilator drug infusion may fluctuate causing transient changes in the infusion delay time. Hemorrhage, patient position changes, cooling and warming of the patient, and changes in anesthesia levels will also effect system (patient) response characteristics.

In light of the complex and highly uncertain nature of system (patient) response characteristics under surgery requiring controls, it is not surprising that reliable system models for many high performance drug delivery systems are unavailable. In the face of such high levels of system uncertainty, robust controllers may unnecessarily sacrifice system per-

formance whereas adaptive controllers are clearly appropriate since they can tolerate far greater system uncertainty levels to improve system performance. In contrast to fixed-gain robust controllers, which maintain specified constants within the feedback control law to *sustain* robust performance, adaptive controllers directly or indirectly adjust feedback gains to maintain closed-loop stability and *improve* performance in the face of system uncertainties. Specifically, indirect adaptive controllers utilize parameter update laws to identify unknown system parameters and adjust feedback gains to account for system variation, while direct adaptive controllers directly adjust the controller gains in response to system variations.

In this research [50], we developed a direct adaptive control framework for adaptive set-point regulation of linear uncertain nonnegative and compartmental systems. As noted in Section 2.15, nonnegative and compartmental dynamical systems are composed of homogeneous interconnected subsystems (or compartments) which exchange variable nonnegative quantities of material with conservation laws describing transfer, accumulation, and outflows between the compartments and the environment. Nonnegative and compartmental models thus play a key role in understanding many processes in biological and medical sciences. Using nonnegative and compartmental model structures, a Lyapunov-based direct adaptive control framework is developed that guarantees partial asymptotic set-point stability of the closed-loop system; that is, asymptotic set-point stability with respect to part of the closed-loop system states associated with the physiological state variables. In particular, adaptive controllers are constructed *without* requiring knowledge of the system dynamics while providing a nonnegative control (source) input for robust stabilization with respect to the nonnegative orthant. Modeling uncertainty in nonnegative and compartmental systems may arise in the system transfer coefficients due to patient gender, weight, pre-existing disease, age, and concomitant medication. Furthermore, in certain applications of nonnegative and compartmental systems such as biological systems, population dynamics, and ecological systems involving positive and negative inflows, the nonnegativity constraint on the control input is not natural. In this case, we also develop adaptive controllers that do not place any restriction on the sign of the control signal while guaranteeing that the physical system states remain in the nonnegative orthant of the state space. Finally, the proposed approach was used to control the infusion of the anesthetic drug propofol for maintaining a desired constant level of depth of anesthesia for noncardiac surgery (see Figures 4 and 5).
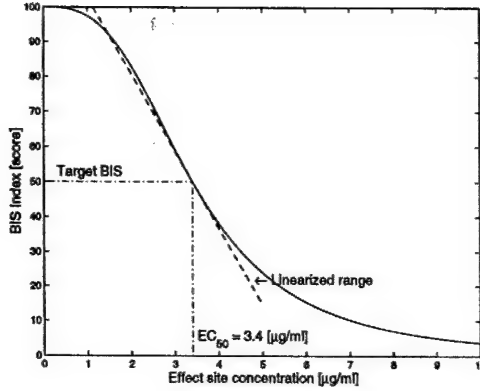
Figure 4: Bispectral (BIS) Index (electroencephalogram (EEG) indicator) versus effect site (brain) concentration. BIS index values of 0 and 100 correspond, respectively, to an isoelectric EEG signal and an EEG signal of a fully conscious patient; while the range between 40 to 60 indicates a moderate hypnotic state.
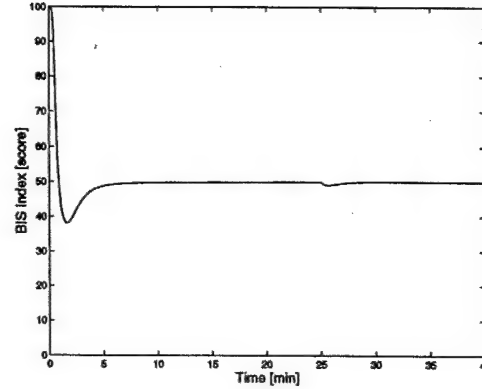
Figure 5: BIS Index versus time achieved by the proposed adaptive controller. The proposed adaptive controller does not require knowledge of the system parameters nor the BIS Index parameters.

2.20. Neural Network Adaptive Control for Nonlinear Nonnegative Dynamical Systems

Neural networks consist of a weighted interconnection of fundamental elements called neurons, which are functions consisting of a summing junction and a nonlinear operation involving an activation function. One of the primary reasons for the large interest in neural networks is their capability to approximate a large class of continuous nonlinear maps. In addition, neural networks have attracted attention due to their inherently parallel architecture that makes it possible to develop parallel weight update laws. This parallelism makes it possible to effectively update a neural network on line. These properties make neural networks a viable paradigm for adaptive system identification and control of complex highly uncertain dynamical systems, and as a consequence the use of neural networks for identification and control has become an active area of research.

In this research [68], we develop a neural adaptive control framework for nonlinear uncertain nonnegative and compartmental systems. The proposed framework is Lyapunov-based and guarantees ultimate boundedness of the error signals corresponding to the physical system states as well as the neural network weighting gains. The neuro adaptive controllers are constructed *without* requiring knowledge of the system dynamics while guaranteeing that the physical system states remain in the nonnegative orthant of the state space. The proposed neuro control architecture is modular in the sense that if a nominal linear design model is available, the neuro adaptive controller can be augmented to the nominal design to account for system nonlinearities and system uncertainty. Furthermore, since in certain applications

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of nonnegative and compartmental systems (e.g., pharmacological systems for active drug administration) control (source) inputs as well as the system states need to be nonnegative, we also develop neuro adaptive controllers that guarantee the control signal as well as the physical system states remain nonnegative for nonnegative initial conditions. We note that neuro adaptive controllers for nonnegative dynamical systems have not been addressed in the literature. Finally, the proposed neuro adaptive control framework is used to regulate the temperature of a continuously stirred tank reactor involving exothermic irreversible reactions.

2.21. Optimal Fixed-Structure Control for Linear Nonnegative Dynamical Systems

In this research [72, 123], we develop optimal output feedback controllers for set-point regulation of linear nonnegative and compartmental dynamical systems. In particular, we extend the optimal fixed-structure control framework to develop optimal output feedback controllers that guarantee that the trajectories of the closed-loop system remain in the nonnegative orthant of the state space for nonnegative initial conditions. The proposed optimal fixed-structure control framework is a *constrained* optimal control methodology that does not seek to optimize a performance measure per se, but rather seeks to optimize performance within a class of fixed-structure controllers satisfying internal controller constraints that guarantee the nonnegativity of the closed-loop system states. Furthermore, since unconstrained optimal controllers are globally optimal but may not guarantee nonnegativity of the closed-loop system states, we additionally characterize domains of attraction contained in the nonnegative orthant for unconstrained optimal output feedback controllers that guarantee nonnegativity of the closed-loop system trajectories. Specifically, domains of attraction contained in the nonnegative orthant for optimal output feedback controllers are computed using closed and open Lyapunov level surfaces. It is also shown that the domains of attraction predicated on open Lyapunov level surfaces provide a considerably improved region of asymptotic stability in the nonnegative orthant as compared to regions of attraction given by closed Lyapunov level surfaces.

2.22. Nonlinear Control of Hammerstein Systems with Passive Nonlinear Dynamics

In this research [31], we develop a nonlinear control design framework for Hammerstein systems with nonlinear passive dynamics. Our main result guarantees global asymptotic

closed-loop stability for nonlinear passive systems with arbitrary input nonlinearities so long as the nonlinear dynamic compensator is modified to include a suitable input nonlinearity. The only restriction on the input nonlinearity is that it be memoryless and that either its characteristics be known or its output be measurable. The proof of this result is based on dissipativity theory [48] and shows that the nonlinear controller modification counteracts the effects of the input nonlinearity by recovering the passivity of the plant and compensator with respect to a modified set of inputs and outputs.

2.23. Stability Margins of Discrete-Time Nonlinear-Nonquadratic Optimal Regulators

The gain and phase margins of continuous-time state feedback linear-quadratic optimal regulators are well known. In particular, in terms of classical control relative stability notions, these controllers possess at least a $\pm 60°$ phase margin, infinite gain margin and 50% gain reduction for each control channel. Alternatively, in terms of absolute stability theory these controllers guarantee sector margins in that the closed-loop system will remain asymptotically stable in the face of a memoryless static input nonlinearity contained in the conic sector $(\frac{1}{2}, \infty)$. In contrast, the stability margins of discrete-time linear-quadratic optimal regulators are not as well known and depend on the open- and closed-loop poles of the discrete-time dynamic system.

Synthesis techniques for discrete-time linear state feedback control laws guaranteeing closed-loop system stability with prespecified sector, gain and phase margins were developed in the literature. However, unlike the continuous-time case, nonlinear-nonquadratic inverse optimal state feedback regulators for nonlinear discrete-time systems possessing guaranteed sector and disk margins to component decoupled input nonlinearities in the conic sector $(\frac{1}{2}, \infty)$ and dissipative dynamic input operators have not been addressed in the literature.

In this research [40], we obtain sufficient conditions for dissipativity with respect to quadratic supply rates. Next, using these extensions, we develop sufficient conditions for gain, sector and disk margin guarantees for discrete-time nonlinear systems controlled by optimal and inverse optimal nonlinear regulators that minimize a nonlinear-nonquadratic performance criterion involving a nonlinear-nonquadratic function of the state and a quadratic function of the feedback control. In the case where we specialize our results to the linear-quadratic case, we recover the classical discrete-time linear-quadratic optimal regulator gain and phase margin guarantees.

2.24. A Unification Between Partial Stability and Stability Theory for Time-Varying Systems

In many engineering applications, *partial stability* (stability with respect to part of the system's states) is often necessary. In particular, partial stability arises in the study of electromagnetics, inertial navigation systems, spacecraft stabilization via gimballed gyroscopes and/or flywheels, combustion systems, vibrations in rotating machinery, and biocenology, to cite but a few examples. For example, in the field of biocenology involving Lotka-Volterra predator-prey models of population dynamics with age structure, if the birth rate of some of the species preyed upon is left alone, then the corresponding population increases without bound while a subset of the prey species remain stable. The need to consider partial stability in the aforementioned systems arises from the fact that stability notions involve equilibrium coordinates as well as a hyperplane of coordinates that is closed but not compact. Hence, partial stability involves motion lying in a subspace instead of an equilibrium point. Additionally, partial stabilization, that is, closed-loop stability with respect to part of the closed-loop system's state, also arises in many engineering applications. Specifically, in spacecraft stabilization via gimballed gyroscopes, asymptotic stability of an equilibrium position of the spacecraft is sought while requiring Lyapunov stability of the axis of the gyroscope relative to the spacecraft. Alternatively, in the control of rotating machinery with mass imbalance, spin stabilization about a nonprincipal axis of inertia requires motion stabilization with respect to a subspace instead of the origin. Perhaps the most common application where partial stabilization is necessary is adaptive control, wherein asymptotic stability of the closed-loop plant states is guaranteed without necessarily achieving parameter error convergence [36, 43].

In this research [41], we present partial stability theorems for nonlinear dynamical systems and present a unification between partial stability theory for autonomous systems and stability theory for nonlinear time-varying systems. This unification allows for time-varying stability theory to be presented as a special case of autonomous partial stability theory so that time-varying and time-invariant stability theory can be discussed in juxtaposition. We stress that our aim was to demonstrate that partial stability and time-varying stability are derivable from the same principles and can be introduced as part of the same mathematical framework without resorting to the more advanced notions of the stability of sets.

2.25. Actuator Amplitude Saturation Control for Systems with Exogenous Disturbances

Since all actuation devices are subject to amplitude limitations, actuator amplitude saturation arises in most control engineering applications resulting in loss of closed-loop performance and, in some cases, in instability. The destabilizing effect of actuator saturation has long been observed in feedback systems with unstable controllers and in particular in feedback systems with integral control action. In this case, since the feedback loop is severed when the actuator saturates the unstable controller modes drift exhibiting a windup effect which, in addition, may lead to a finite escape time instability. The problem of actuator saturation is further exacerbated by system uncertain exogenous disturbances. Thus, the control system design process must account for amplitude saturation as well as for system disturbances.

There exists an extensive literature devoted to the control saturation problem and the associated windup problem. However, the saturation controllers developed in the literature do not account for the effect of exogenous disturbances. In this research [42], we develop an absolute stabilization framework to address the actuator amplitude saturation control problem for systems with bounded energy L_2 exogenous disturbances. Specifically, we construct a modified Riccati equation whose solution guarantees that the closed-loop undisturbed system is globally asymptotically stable in the face of sector bounded input nonlinearities and the closed-loop output system energy is less than the net weighted input system energy at any time T in the face of L_2 disturbances. Using the modified Riccati equation, constructive sufficient conditions for fixed-order (i.e., full- and reduced-order) dynamic compensators guaranteeing amplitude saturation constraints and disturbance rejection are developed. In addition, to account for closed-loop system performance, we also consider the minimization of a quadratic performance criterion involving weighted state and control variables over the allowable class of input nonlinearities.

2.26. Nonlinear Adaptive Tracking of Surface Vessels with Exogenous Disturbances

The desire for developing a control design methodology for surface vessel maneuvering and position tracking has led to significant activity in modeling and control of marine vehicles. Early conventional vessel control design for dynamic positioning of ships were developed under the assumption that the kinematic and dynamic equations of motion can be linearized, so that linear optimal control theory is applicable. However, for vessel tracking applications

wherein the surge and sway positions and yaw angle must be controlled simultaneously, a linearized model is not valid. In this research [46], we develop a coupled nonlinear two-vessel tracking model for a leading-tracking vessel configuration. The unknown interaction disturbances acting on the vessels are modeled as known functions with unknown parameters. Next, an adaptive control law is designed to attenuate the interaction disturbances and maintain a desired separation of the two vessels, where the leading vessel serves as the reference for the tracking vessel. Here, the desired reference trajectory is generated by a Nomoto reference model. The proposed inverse optimal adaptive controllers are compared with a standard adaptive backstepping design and a locally optimal and robust backstepping design. This comparison demonstrates that the inverse optimal adaptive controller uses less control effort and achieves better tracking as compared with the other designs.

2.27. Exponentially Dissipative Dynamical Systems: A Nonlinear Extension of Strict Positive Realness

One of the most basic issues in system theory is stability of feedback interconnections. Two of the most fundamental results concerning stability of linear feedback systems are the positivity and small gain theorems. The positivity theorem states that if G and G_c are (square) positive real transfer functions, one of which is strictly positive real, then the negative feedback interconnection of G and G_c is asymptotically stable. Alternatively, the small gain theorem implies that if G and G_c are asymptotically stable finite gain transfer functions, one of which is strictly finite gain so that $\|G\|_\infty \|G_c\|_\infty < 1$, then the negative feedback interconnection of G and G_c is asymptotically stable. In an attempt to generalize the above feedback interconnection stability results to nonlinear state space systems, Hill and Moylan introduced the novel concepts of input strict passivity, output strict passivity, and input-output strict passivity using notions of storage functions with appropriate supply rates from dissipativity theory for nonlinear dynamical systems. In particular, Hill and Moylan show that if the nonlinear dynamical systems G and G_c are both input strict passive, or both are output strict passive, or G is passive and G_c is input-output strict passive, then the negative feedback interconnection of G and G_c is asymptotically stable. However, these nonlinear feedback stability results do not represent an exact nonlinear extension to the positivity and small gain theorems discussed above. Specifically, specializing the notions of input strict passivity, output strict passivity, and input-output strict passivity to linear systems yields stronger conditions than strict positive realness and strict bounded realness.

In this research [48,85], we extend the notion of dissipative dynamical systems to formalize the concept of the nonlinear analog of strict positive realness and strict bounded real-

ness. In particular, using exponentially weighted system storage functions with appropriate exponentially weighted supply rates we introduce the concept of exponential dissipativity. Furthermore, we develop nonlinear Kalman-Yakubovich-Popov conditions for exponentially dissipative dynamical systems with quadratic supply rates. In the special cases where the system dynamics are linear and the quadratic supply rates correspond to the net system power, and the weighted input and output system energy, the Kalman-Yakubovich-Popov conditions specialize to the strict positive real lemma and strict bounded real lemma, respectively.

Furthermore, using exponential dissipativity concepts we present several stability results for nonlinear feedback systems that provide a nonlinear analog to the classical positivity and small gain theorems for linear feedback systems. In addition, using the extended Kalman-Yakubovich-Popov conditions for exponentially passive systems, we extend the H_2-based positive real controller synthesis methods to nonlinear passive dynamical systems. Specifically, globally stabilizing static and dynamic exponentially passive output feedback nonlinear controllers are constructed for nonlinear passive systems that additionally minimize a nonlinear-nonquadratic performance criterion involving a nonlinear-nonquadratic, nonnegative-definite function of the state and a quadratic positive-definite function of the control. In particular, by choosing the nonlinear-nonquadratic weighting functions in the performance criterion in a specified manner, the resulting static and dynamic controllers are guaranteed to be exponentially passive. In the dynamic output feedback case, we show that the linearized controller for the linearized passive system is H_2 optimal.

2.28. Linear Controller Analysis and Design for Systems with Input Hystereses Nonlinearities

In recent years the desire to orbit large, lightweight space structures with high-performance requirements has prompted researchers to consider actuators which possess a fraction of the size and weight of more conventional actuation devices. As a consequence, considerable research interest has focused in the field of smart or adaptive materials as a viable alternative to conventional proof mass actuators for vibration control. Due to the fact that adaptation in smart materials is a result of physical nonlinear changes occurring within the material, these actuation devices exhibit significant hysteresis in the actuator response. Specifically, smart distributed actuators such as shape memory alloys, magnetostrictives, electrorheological fluids, and piezoceramics all exhibit hysteretic effects. Since hystereses nonlinearities can severely degrade closed-loop system performance, and in some cases drive the system to a limit cycle instability, they must be accounted for in the control-system design process.

Even though numerous models for capturing hystereses effects have been developed, with the Preisach model being the most widely used, controller analysis and synthesis for feedback systems with hystereses nonlinearities has received little attention in the literature. The main complexity arising in hystereses nonlinearities is the fact that every reachable point in the input-output hysteresis map does not correspond to a uniquely defined point. In fact, at any reachable point in the input-output hysteresis map there exists an infinite number of trajectories that may represent the future behavior of the hysteresis dynamics. These trajectories depend on a particular past history of the extremum values of the input. However, hystereses nonlinearities with counterclockwise loops have been shown to be dissipative with respect to a supply rate involving force inputs and velocity outputs. Dissipative hystereses models include the well known backlash nonlinearities, stiction nonlinearities, relay hystereses, and most of the hystereses nonlinearities arising in smart material actuators.

The contribution of this research [53, 87] is a methodology for analyzing and designing output feedback controllers for systems with input hystereses nonlinearities. Specifically, by transforming the hystereses nonlinearities into dissipative input-output dynamic operators, dissipativity theory is used to analyze and design linear controllers for systems with input hystereses nonlinearities. In particular, by representing the input hysteresis nonlinearity as a dissipative input-output dynamical operator with respect to a given supply rate, partial closed-loop asymptotic stability; that is, asymptotic stability with respect to part of the closed-loop state associated with the plant and the controller, is guaranteed in the face of an input hysteresis nonlinearity. Furthermore, it is shown that the reminder of the state associated with the hysteresis dynamics is semistable; that is, the limit points of the hysteretic states converge to Lyapunov stable equilibrium points determined by the system initial conditions.

2.29. A Lyapunov Function Proof of Poincaré's Theorem

Poincaré's theorem provides a powerful tool in analyzing the stability properties of periodic orbits and limit cycles of n-dimensional dynamical systems in the case where the trajectory of the system can be relatively easily integrated. Specifically, Poincaré's theorem provides necessary and sufficient conditions for stability of periodic orbits based on the stability properties of a fixed point of a discrete-time dynamical system constructed from a Poincaré return map. In particular, for a given candidate periodic trajectory, an $(n-1)$-dimensional hyperplane is constructed that is transversal to the periodic trajectory and which defines the Poincaré return map. Trajectories starting on the hyperplane which are sufficiently close to a point on the periodic orbit will intersect the hyperplane after a

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time approximately equal to the period of the periodic orbit. This mapping traces the system trajectory from a point on the hyperplane to its next corresponding intersection with the hyperplane. Hence, using system analytic arguments along with the somewhat involved Hartman-Grobman theorem, the Poincaré return map can be used to establish a relationship between the stability properties of a dynamical system with periodic solutions and the stability properties of an equilibrium point of an $(n-1)$-dimensional discrete-time system. In this research [62, 110], using the notions of Lyapunov and asymptotic stability of sets, we construct lower semicontinuous Lyapunov functions to provide a Lyapunov function proof of Poincaré's theorem.

2.30. A Dissipative Dynamical Systems Approach to Stability Analysis of Time Delay Systems

Modern complex engineering systems involve a multitude of information and communication networks. A key physical limitation of such systems is that power transfers between interconnecting system components are not instantaneous and realistic models for capturing the dynamics of such systems should account for information in transit. To accurately describe the evolution of these complex systems, it is necessary to include in any mathematical model of the system dynamics some information of the past systems states. This leads to (infinite-dimensional) delay dynamical systems. Time-delay dynamical systems have been extensively studied in the literature. Since time delay can severely degrade system performance and in many cases drive the system to instability, stability analysis of time delay dynamical systems remains a very important area of research. A key method for analyzing stability of time delay dynamical systems is Lyapunov's second method as applied to functional differential equations. Specifically, stability analysis of a given linear time delay dynamical is typically shown using a Lyapunov-Krasovskii functional. Standard Lyapunov-Krasovskii functionals involve a fixed quadratic function and an integral functional explicitly dependent on the system delay. As in classical absolute stability theory, the fixed quadratic part of the Lyapunov-Krasovskii functional is associated with the stability of the forward delay-independent part of the retarded dynamical system. However, the system theoretic foundation of the integral part of the Lyapunov-Krasovskii functional is less understood.

In this research [64, 117], using the notions of dissipativity and exponential dissipativity theory, we present sufficient conditions for guaranteeing asymptotic stability of time delay dynamical systems. Specifically, representing a time delay dynamical system as a negative feedback interconnection of a finite-dimensional linear dynamical system and an infinite-dimensional time delay operator, we show that the time delay operator is dissipative with

respect to a quadratic supply rate and with a storage functional involving an integral term which is identical to the integral term appearing in the Lyapunov-Krasovskii functional. Next, using stability of feedback interconnection results based on dissipativity of a feedback interconnected system, we develop sufficient conditions for asymptotic stability of time delay dynamical systems that are consistent with the results in the literature yet providing a system theoretic foundation for the Lyapunov-Krasovskii functional forms. The overall approach provides an explicit framework for constructing Lyapunov-Krasovskii functionals for asymptotically stable time delay dynamical systems based on the dissipativity properties of the time delay operator. Finally, analogous results for discrete-time systems are also presented.

2.31. Adaptive Control for Thermoacoustic Combustion Instabilities

High performance aeroengine afterburners and ramjets often experience combustion instabilities at some operating condition. Combustion in these high energy density engines is highly susceptible to flow disturbances, resulting in fluctuations to the instantaneous rate of heat release in the combustor. This unsteady combustion provides an acoustic source resulting in self-excited oscillations. In particular, unsteady combustion generates acoustic pressure and velocity oscillations which in turn perturb the combustion even further. These pressure oscillations, known as thermoacoustic instabilities, often lead to high vibration levels causing mechanical failures, high levels of acoustic noise, high burn rates, and even component melting. Hence, the need for active control to mitigate combustion induced pressure instabilities is severe.

Due to the intricate complex physical phenomena in combustion processes involving acoustics, thermodynamics, fluid mechanics, and chemical kinetics, finite dimensional linear or nonlinear models are unavoidably inaccurate. Basic system data such as damping, frequency, and mode shapes are often poorly known. Furthermore, approximations of pressure and velocity fluctuations involving time-averaging in the governing system equations result in further system uncertainty that manifests itself as highly structured constant real parametric uncertainty in the modal frequencies and damping. Thus for pressure oscillation suppression in combustion processes, system modeling uncertainty necessitates the need for nonlinear adaptive control.

In this research [97], we apply the Lyapunov-based direct adaptive control framework developed in [36] to suppress the effects of thermoacoustic instabilities in combustion processes. The overall framework demonstrates that the proposed adaptive controllers provide consid-
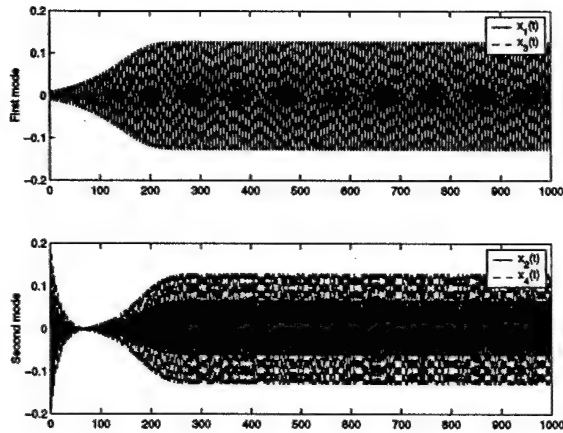
Figure 6: Open-loop state response of an uncontrolled two-mode combustion model.
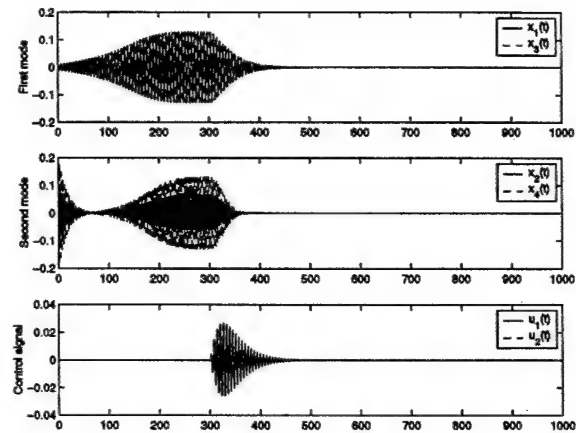

Figure 7: These plots illustrate the removal of energy from a two-mode uncertain combustion model with 8709% deviation in nominal system parameters.

erable robustness in suppressing thermoacoustic combustion instabilities in the presence of parametric uncertainties in the model (see Figures 6 and 7).

3. Research Personnel Supported

Faculty

Wassim M. Haddad, Principal Investigator

Graduate Students

Sergei G. Nersesov, Ph. D

Joseph R. Corrado, Ph. D

Natasă A. Kablar, M.S.

Several other students (T. Hayakawa, A. Leonessa, J. Oh, T. Rajpurohit, and E. August) were involved in research projects that were closely related to this program. Although none of these students were financially supported by this program, their research did directly contribute to the overall research effort. Furthermore, two Ph. D. Dissertations were completed under partial support of this program; namely

A. Leonessa, *Hierarchical Robust Nonlinear Switching Control Design for Propulsion Systems*, Ph. D. Dissertation, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA, November 1999.

J. R. Corrado, *Robust Fixed-Structure Controller Synthesis*, Ph. D. Dissertation, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA, August 2000.

The first of the Ph. D. students, Dr. Leonessa, holds the rank of Assistant Professor of Ocean Engineering at Florida Atlantic University, while the second of the Ph. D. students, Dr. Corrado, is presently with the Raytheon Missile Systems, Tucson.

4. Interactions and Transitions

4.1. Participation and Presentations

The following conferences were attended over the past three years.

IEEE Conference on Control Applications, Kohala Coast, HI, August 1999.

IEEE Conference on Decision and Control, Phoenix, AZ, December 1999.

American Control Conference, Chicago, IL, June 2000.

IEEE Mediterranean Conference on Control and Automation, Patras, Greece, July 2000.

ASME International Mechanical Engineering Congress and Exposition, Orlando, FL, November 2000.

American Control Conference, Arlington, VA, June 2001.

ASME International Mechanical Engineering Congress and Exposition, New York, NY, November 2001.

IEEE Conference on Decision and Control, Orlando, FL, December 2001.

American Control Conference, Anchorage, AK, May 2002.

Conference on Decision and Control, Las Vegas, NV, December 2002.

Furthermore, conference articles [76–114] were presented.

4.2. Transitions

Computational work on fixed-architecture control supported by this program has been transferred to Raytheon Missile Systems, Tucson, under the supervision of Dr. J. R. Corrado (520-794-1662) to transition our analytical work on robust fixed-structure control to industry programs. Specifically, in collaboration with D. S. Bernstein at the University of Michigan, we have been developing a *Robust Fixed-Structure Control Toolbox* integrated within the MATLAB® environment that can be used to synthesize fixed-structure controllers that are optimal with respect to given performance measures, and at the same time satisfy stability and robustness constraints. The *Robust Fixed-Structure Control Toolbox* focuses on the development of a control design algorithm which supports the following paradigm: Minimize

control law complexity subject to the achievement of a specified accuracy in the face of a specified level of uncertainty.

Our recent analytical work on biological and physiological systems supported by this program was communicated to Dr. J. M. Baily (404-778-3957) at the Department of Anesthesiology, Emory University Hospital, Atlanta, GA 30322. This has sparked a close collaboration between the Principal Investigator and Dr. Bailey that has resulted in several research publications, several internal Georgia Tech-Emory proposals as well as a National Institute of Health proposal. The main goal of this collaboration is to eliminate the steep barriers to communication between control engineering and medicine and advance the state-of-the-art in active control of drug delivery systems for clinical pharmacology. While our application objective in this collaboration is to develop active control methods to deliver sedation to critically ill patients, our research will have implications for other uses of closed-loop control of drug delivery. There are numerous potential applications such as control of glucose, heart rate, blood pressure, etc., that may be improved as a result of this research program.

5. Research Publications

5.1. Journal Articles

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